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DEVELOPMENT OF LOW FREQUENCY
UNDERWATER SOUND EQUIPMENT
R. L. Mills

FINAL REPORT ON CONTRACT NONR-680(00)
June 25, 1954

The research reported in this document
was done under ONR Contract No. 680(00)
between the Office of Naval Research
and the Magnolia Petroleum Company.

Magnolia Petroleum Company
Field Research Laboratories
Dallas, Texas

Report by

R. L. Mills

Approved for Distribution

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ABSTRACT

Two systems which satisfactorily utilize signals from geophones and hydrophones operated at the same point in an underwater sound field have been developed under Contract Nonr-630(00) with the Field Research Laboratories of the Magnolia Petroleum Company in Dallas, Texas. In one of the systems the directional components of water particle velocity caused by a water-borne sound wave are measured by a three directional cluster of geophones. A low frequency hydrophone measures sound pressure at the same point. Multipliers then produce voltages proportional to the average values of the products of the pressure signal and each of the velocity signals. These voltages represent the components of sound intensity at the detectors and are combined to give both the amplitude and direction of the net energy flow, or intensity, of the sound field. The nature of energy flow from a source is such that when the system gives the direction of the vector it points to the source. The intensity meter, therefore, can be used as a passive listening device. Small detectors, the measurement of net, rather than instantaneous, energy flow and operation in the frequency band between 20 and 500 cps give this intensity measuring system features that make it attractive for several long range listening applications.

The other system developed under the contract is one in which a low frequency hydrophone and a single vertically sensitive geophone are operated at the same point. Pressure and velocity signals are then compared directly to find specific acoustic impedance to a vertically traveling wave. The system is convenient to use, and it is suitable for finding bottom and other reflector impedances where water depth and other factors prevent the use

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of more standard instruments and techniques. Signal processing equipment was developed so both impedance amplitudes and phase angles could be found at all frequencies between 20 and 500 cps with a minimum of mathematical computations. Simple modification of the underwater detectors would make the instrument suitable for measuring the impedance of ships hulls and other vertical reflecting surfaces.

Development of these new instruments, the intensity meter and the impedance meter, involved not only some preliminary field tests which demonstrated the usefulness of the instruments but also the design of several special components required for assembling the systems. This final report which summarizes the accomplishments under the contract, therefore, does not deal with just test results but also describes briefly the special circuits and techniques that were devised.

Details of the phases of the project have been reported previously in separate technical reports. This is a summary of all the other reports. It points out the accomplishments on all phases of the work and discusses the possible usefulness of the new circuits and methods in other systems. It also serves as a descriptive index of the previous technical reports.

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DEVELOPMENT OF LOW FREQUENCY UNDERWATER SOUND EQUIPMENT

I. INTRODUCTION

Under Contract Nonr-680(00) the Field Research Laboratories of the Magnolia Petroleum Company in Dallas have developed two systems for use in low frequency underwater sound work. The first measures the intensity of traveling sound waves. The other uses sound waves in the measurement of the specific acoustic impedance of sea bottoms and hull structures.

Both of these are expected to be useful as instruments in fundamental studies of sound transmission and reflection. In addition, the intensity meter is expected to be useful as a practical, low frequency, directive, listening device. It indicates not only the amplitude but also the direction of the sound intensity vector at any point in a sound field. This vector's direction is the same as that of the sound energy emanating radially from a source. Therefore, by finding its direction the direction to the source is found. The intensity meter, therefore, can be used in military applications for finding the bearings to distant ships and other sound sources of tactical importance.

The contract supported the intensity meter development because the system promised to have several features that would make it particularly attractive for low frequency listening. A single, small assembly of detectors that operate in the frequency band between 20 and 500 cps was proposed for use in the system. No need was anticipated for rotating or moving this detector assembly to find the bearing to a principle sound source in any direction. This would make the system more convenient than those employing spaced pressure detectors for directivity. Also, the system promised to operate satisfactorily

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when the ratio of noise from a discrete source (a ship, for example) to the noise from randomly distributed background sources was low. This suggested that distant ships producing a very weak signal at the detectors could be detected even when a high ambient noise level is produced by a high sea state or some other factor. Other promised advantages of the system included an output display that could be accurately interpreted by untrained operators and facilities for bucking out the masking effects of steady noise from the ship on which the detectors were mounted. Under the contract, the degree to which these advantages could be realized in an actual system was investigated.

The impedance meter's development stemmed from a request by the Acoustics Branch of the ONR. The request was to construct a system for measuring impedance with detectors similar to those developed for use with the intensity meter.

This system, too, has features that make it attractive for its intended use. The small underwater detectors make it convenient to move the system about for measuring impedance at different points and they make it possible to use a direct method of measuring impedance at each point. The method permits measuring single-point impedance within the frequency band from 20 to 500 cps without moving the detectors. The instruments designed for using the method make it possible to calculate impedance amplitudes from the ratio of two meter readings and to read impedance phase angles directly.

Both the intensity meter and the impedance meter operate on principles that have never been used before in underwater sound work. When these systems are used, intensity and impedance are found from the relationship between the fundamental sound field properties, pressure and particle velocity, at a

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single point. Simultaneous measurements of these quantities are made at a point by the underwater detectors and then voltages from the detectors are processed to form the desired output quantities. In the intensity meter a quantity proportional to the average product of the pressure and velocity signal is produced. In the impedance meter the ratio of sinusoidal components of the pressure and velocity signals is found. Developing these systems, therefore, necessitated designing not only special underwater detectors but also two sets of special electronic components for performing the two different computations. Components designed for computation in the intensity meter included means for multiplying the complex detector signals and means for using these products to produce a directional indication of the total sound intensity vector at the point of measurement. Computational equipment for the impedance meter included means for separating particular frequency components from the other components of the complex signals from both the pressure and velocity detectors and means for measuring the amplitudes of the components of both signals at any selected frequency. Taking the ratio of the measured amplitudes then yields the amplitude of the impedance at that frequency. The phase angle between the pressure and velocity signal components at any frequency is read directly from a calibrated control used in the process of finding the component amplitudes.

Another phase of the work under the contract was testing the systems in the field. Only a few tests were conducted on the impedance meter in order to show that the system operated as intended. However, the intensity meter was tested more extensively. It was preliminarily evaluated for two specific

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military applications. In one series of tests it was operated aboard a submarine. Its suitability as a passive, long range, directive detector of low frequency sound sources was demonstrated. In another series of tests it was studied as a possible system for use in harbor defense work. Satisfactory operation of the system in response to transitory acoustic signals caused by splashes from aerially laid mines was observed. Work on this, the test phase of the project, showed that actual systems would operate on the principles proposed for use, and showed that such systems have the attractive, theoretically predicted characteristics.

In order to give a complete picture of the work on all phases of the project, accomplishments on each phase are reported here. This final report describes the special instruments and design techniques which were successfully developed and discusses the procedures and results of field tests on the completed systems. In doing this the report summarizes previously published technical reports giving details on the main phases. In addition it briefly describes other component developments and laboratory tests on the system which were not previously reported. These latter accomplishments are reported here in order to make the report complete. They concern a multiplication method not ultimately used in the system, and the signal amplifiers, the power supplies, the input and output test panels, and the display system used in the intensity meter. Considerable time was spent developing these units but describing them was postponed until now because each was considered to be minor from the standpoint of having wide usefulness in other systems. However, they are not minor from the standpoint of giving the intensity measuring system desirable characteristics.

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II. PREVIOUSLY PUBLISHED TECHNICAL REPORTS

The following is a list of previously published technical reports which will be referred to by their "dash numbers" in the remainder of this report.

A. Reports on Component Developments

1. Technical Report No. 680(00)-4, "A New Electronic Multiplication Method Involving Only Simple, Conventional Circuits", by R. L. Mills, November 9, 1953 (Unclassified). (This was also circulated through the company as a Laboratory Report.)

2. Technical Report No. 680(00)-6, "Compass Dial Bearing Indicator for Acoustic Signals", by S. N. Heaps, February 22, 1954 (Confidential).

3. Technical Report No. 680(00)-7, "Low Frequency Detectors of Underwater Sound", by S. N. Heaps, April 20, 1954 (Confidential).

B. Reports on Tests of Intensity Meter System

1. Confidential Navy Memorandum No. Nonr-680(00)-1 to Wilbert Annis, ONR (Code 420) dated October 15, 1952.

2. Technical Report No. 680(00)-1, "First Sea Tests of the Underwater Acoustic Intensity Meter", by J. E. White, January 26, 1953 (Confidential).

3. Technical Report No. 680(00)-5, "Report on Tests of the Underwater Sound Intensity Meter for Locating Transitory Sources", by R. L. Mills, January 18, 1954 (Confidential).

C. Report on Impedance Measuring System

1. Report No. 680(00)-8, "A Simple System for Measuring Specific Acoustic Impedance of Underwater Reflectors at Low Frequencies", by Joseph Zemanek, Jr., May 20, 1954 (Confidential).

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D. Reports on Theoretical Studies

Technical Reports Nos. 680(00)-2 and -3, "A Study of the Scattering of Sound Waves in Fluids", Part I and Part II (Confidential), by F. C. Karal, June 10, 1953. These are mathematical investigations of the possible effects of hull structures on the intensity of sound waves in the immediate neighborhood of the structure. Since this work was only indirectly related to the actual development program, these reports are not summarized in the following sections. The investigations were conducted to determine whether or not intensity meter direction indications would be accurate when the detectors were mounted close to the hull of a ship. For the analysis, the hull was assumed to be a spherical pressure release surface immersed in an infinite perfect fluid. Deviations in the direction of the intensity of a horizontally traveling sound wave due to this scatterer were calculated. It was found that they were small at points outside the surface on a vertical line through the center of the sphere. This led to the conclusion that the intensity meter would probably indicate the direction of the traveling wave accurately even when the detectors were close to a ship's hull. The actual hull could be expected to have less effect than the extreme and obviously unrealistic surface considered in the analysis. Further theoretical work on this subject planned at the time these reports were published was not done.

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III. DISCUSSION

Discussion of the project is divided into two sections. The first deals with the development of the intensity meter system. Most of the work was devoted to this system and it is the most important because it can be used in tactical applications. The second briefer section concerns the impedance meter which has been described completely in a previous report.

A. The Intensity Meter Development

1. General

At the time support for the intensity meter development was requested, the system was only an idea that could be represented by an operational block diagram such as the one shown in Figure 1. The object of the development was to assemble actual components that would perform the indicated operations and to show that the assembled system would behave as predicted.

If the system could have been assembled from standard parts, a list of accomplishments under the contract would have been limited to the facts demonstrated by the system tests. But this was not the case. Practically every operation in processing the detector signals required an instrument that was not commercially available and, therefore, necessitated one that had to be specially designed. Hence, the list of accomplishments would be incomplete without mention of these special design and construction efforts so the complete system will be described here.

The functions performed by the components are the ones required to measure the mutually perpendicular components of sound intensity at a point and then to produce representations of vectors which are combinations of these

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components that indicate both the azimuth and elevation angle of the total vector. In the detector assembly one unit generates voltages proportional to sound pressure at a point. Three other units in the assembly generate voltages proportional to the three mutually perpendicular directional components of water particle velocity at the same point. For convenience in interpreting data two of these units are oriented to measure the components of velocity in a horizontal plane. The third measures the vertical component. The assembly is operated with the detectors free to move with the water and isolated from vibrations of any supporting structure. The component, labeled "compensator" in Figure 1, is an electronic circuit which counteracts the differences in the operation of the velocity and pressure detectors. It makes the voltages applied to the signal amplifiers have the same relationship to each other that the acoustical quantities have to each other in the water. This proper relationship is maintained as identical signal amplifiers raise the signal levels and filter out undesired signal frequency components. In the multipliers the pressure signal multiplies each of the velocity signals separately and output filters produce dc voltages proportional to the average values of the instantaneous products. Thus voltages which represent the amplitudes of the components of intensity in the three mutually perpendicular directions established by the velocity detectors are produced. In the display apparatus the component voltages are added vectorially and this sum is indicated. The indication is such that the direction of the total intensity vector relative to the velocity detector axes is obvious. The true bearing to the source producing the vector can be found then by correcting the relative bearing indication for the bearing of the velocity detector axes. The true bearing of these axes

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is determined by independent means as the detectors are installed.

2. System Component Developments

Separate system components consist of the equipment for performing the sound detection operations, the compensating operation, the signal amplifying and filtering operations, and the multiplication and display operations. Characteristics of these components plus the power supplies and some special test systems which make the units suitable for use in the intensity meter system will be pointed out. Their general characteristics will be discussed also because most of the individual units are suitable for use in other systems. Also, several novel techniques were used which may be useful in other design applications.

a. Underwater Detectors

Report No. 7 discusses the requirements of the underwater detector assembly, the sensing elements used, and the mounting and supporting methods that make the assembly satisfy the requirements. The main requirement was that the assembly be small but sensitive to the directional components of water particle velocity and the variations in pressure produced at a single point by sound with frequency components between 20 and 500 cps. The detectors were also to be unresponsive to other than water-borne sound. A hollow barium titanate cylinder was used as the pressure sensing element, and a cluster of standard seismic geophones were used to measure the velocity components. An impedance matching, electronic pre-amplifier needed for good low frequency response of the pressure detector was mounted inside the barium titanate cylinder. This permitted the pressure detector to be small.

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The use of geophones made the velocity detector small. In fact, it necessitated keeping it small. Geophones accurately measure the directional components of velocity only when the acoustical wave length is much larger than the dimensions of the detector. To satisfy this desirable requirement three 1-5/8 inch diameter by 1-5/8 inch long cylindrical geophones were mounted inside a cylindrical aluminum can approximately six inches in diameter and eight inches long. The orientations of the geophones were fixed so that the axes of maximum sensitivity were all perpendicular. The axis of one geophone was made vertical; the other two were horizontal but at right angles to each other.

The principle purpose of the enclosing can was to insulate the geophones electrical terminals from the water. However, its size and shape, the method of mounting the geophones in it, and the method of supporting it so the geophones would measure only water particle velocity were not arbitrarily chosen. The can was made cylindrical so forces from any horizontal direction would have the same effect on its motion. It was made large enough to entrap sufficient air with the geophones inside to make the assembly light in comparison to water so appreciable motion would result from motion of the surrounding water. The geophones were mounted in the can in such a way that tilting and turning would not result from linear water particle motion. Two support points for the whole assembly were provided so that its orientation would remain fixed after the unit had been installed. It was suspended from a stationary supporting structure by means of elastic shock cords. The elasticity of these cords provided isolation of the detectors from vibration of the supporting structure, and their flexibility permitted the detectors to move with the

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surrounding water.

The velocity detector assembly and the pressure detector were operated as close together as possible without actually touching. This was done so they would measure sound field properties at effectively the same point. It was accomplished by suspending the pressure detector from the same cords supporting the velocity detectors. This not only placed the detectors close together but it increased the effectiveness of the shock mounting arrangement also.

Satisfactory operation of the whole intensity meter system indicated that the underwater detectors fulfilled their requirements. Geophone output voltages due to vibrations other than those of the local water particles would have produced uninterpretable results. Such results were not obtained.

The fact that electromechanical velocity detectors such as geophones are rarely used for measuring the properties of water-borne sound suggests that previous attempts to do so may have been unsuccessful. If such is the case, use of them in the intensity meter represents the first successful application. This then is a noteworthy achievement under the contract.

This accomplishment is believed to have been made possible by proper design of the geophone assembly and by operating the detectors so they were not disturbed by spurious ground motion or vibration of the supporting structures. If other attempts are made to use geophones in water, a similar detector design and a comparable operating technique is recommended. If this recommendation is followed, the geophone promises to be attractive for use in

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several systems. It is quite small but it is sensitive and directive at low frequencies and neither its sensitivity nor its directivity changes with frequency over the band in which it operates. Also, its ruggedness which has made it so popular in the geophysical industry would be an asset in underwater sound work.

b. Compensating Circuit

The compensating circuit performs a function made necessary by the fact that time lags which are not duplicated in the pressure detector are produced in the geophones. It introduces lag in the pressure channel to make the pressure and velocity channels have similar frequency characteristics. When this is done the voltages at comparable points in the channels have the same relationships as the acoustical variations causing them and the product of the voltages validly represents the sound intensity vector at the detectors.

Only the phase characteristic of the pressure channel is changed; so a single circuit provides all the compensation needed by the entire system. The circuit used for this purpose is an all-electrical analogue of the three identical electromechanical geophones which produce the signals in the velocity channels. At every frequency in a wide band this circuit produces a lag between its output and input voltages which equals the lags between the geophone output voltages and the particle velocity causing the outputs. Since the pressure detector output voltage is in phase with the pressure variations (within the frequency range of interest) adding the phase lags of the geophones equivalent circuit to the pressure channel produces just the desired total phase shift.

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The section on the compensating circuit in Report No. 8 applies also to the compensating circuit used in the intensity measuring system. It includes instructions for measuring geophone characteristics of importance to the compensating circuit design procedure, an explanation of how both the circuit configuration and values for the electrical circuit elements can be derived from the geophone characteristics, and also it presents test data showing the accuracy of the compensation achieved by means of the circuit.

The design of this circuit is considered to be another noteworthy achievement under the contract. It represents the application of the theory of the analogy between electrical and electromechanical systems for the solution of an unusual design problem. The circuit is essential to the proper operation of both the intensity meter and the impedance meter, and the use of a similar one is recommended whenever it is important to maintain a fixed relationship between signals from pressure detectors and geophones.

c. Signal Amplifiers

Once proper relationships between the pressure and velocity signals are established in the system they are maintained as the signals are amplified and filtered. All channel amplifiers are effectively identical. With similar filter settings all of them produce the same phase shift within plus or minus two degrees, and with similar attenuator settings the gains are the same within plus or minus 0.1 db.

The amplifiers were designed to be extremely flexible so the system operation can be studied under a wide variety of signal amplitude and frequency conditions. Full amplifier gain, including that of the input transformers which match the detectors to the first amplifying stage, is 150 db.

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This can be reduced by means of front panel controls in calibrated 2 db steps to 4 db. The 3 cps to 1500 cps pass band can be reduced with independent adjustable high and low cutoff filters. The lower end of the pass band can be set by means of front panel controls at approximately one-half octave frequency steps between 20 and 300 cps. The upper end can be set at frequencies between 35 and 400 cps. In the filter attenuation band the attenuation is 13 db per octave. With the filter controls, signal frequency components in several bands can be successively selected for separate study. With the gain controls, detector signals with amplitudes at any level within the dynamic ranges of the detectors can be set at the level needed to produce optimum operation of succeeding components in the system.

Features to insure stable reliable operation and to make maintenance simple and rapid were also incorporated in the amplifiers. Complete amplifying stages with vacuum tubes and other circuit components were made identical and were assembled for ease of replacement on plug-in units. Each amplifier contains three of these units. The gain of each was precisely set at 40 db. A feed back circuit was used so the gain would depend to a minimum degree on changes of vacuum tube characteristic with age, plate supply voltage fluctuations, and filament voltage variations. If a unit appears to be operating improperly, it is simply removed and a spare unit is inserted in its place.

The characteristics of these amplifiers undoubtedly contributed to the successful operation of the system. Probably their most unique feature, one that might make them especially attractive for use in other systems, is the input transformers. These transformers match the 210 ohm geophones to a 1,000,000 ohm input grid resistor over the entire frequency band between 3 and 1500 cps.

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d. Multiplication and Display Apparatus

(1) General

The multiplication and display apparatus contains means for using the signal amplifier output voltages to produce voltages proportional to the directional components of the sound intensity at the underwater detectors and means for using these to produce a visual indication of the direction of the total intensity vector. The components are obtained by multiplying each velocity signal voltage by the pressure signal voltage separately. These components are combined to produce the total vector indication in a manner such that the direction of the total vector relative to the component directions can be obtained directly.

In general the total intensity vector can point in any direction in space and an indicator for showing its direction would have to have three dimensional indications. Such an instrument was not feasible so two separate indications which are sufficient to completely describe the vector are presented. In one the projection of the vector on a horizontal plane is displayed; in the other the vector's projection on a vertical plane presumed to contain both the sound source and the detectors is displayed. The second indication is of the total intensity vector but only the elevation or declination angle to the source can be found. The first indication is of the horizontal component of the vector. This gives the azimuthal bearing to the sound source.

Both of these are required to definitely locate a source which may be above or below the detectors. However, if only the azimuthal

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bearing to a sound source is desired the second indication can be omitted. This eliminates the need for measuring the vertical component of intensity and the underwater velocity detector assembly need contain only two horizontally sensitive geophones. This type of detector was used in most tests on the intensity meter and only azimuthal bearings to the sources were found. But facilities for measuring the elevation angle also were included in the display apparatus.

The total horizontal component and the entire vector are displayed in a similar manner. Either can be shown on the same instrument by changing the voltages applied to the instrument. A pointer that rotates about the center of the circular face of the indicating instrument is made to represent the vector being displayed. This is accomplished by making the pointer's projections on two perpendicular axes that intersect at the center of the instrument face be proportional to the amplitudes of the vector components. The pointer then represents the vector sum of the components and hence the total vector. When the horizontal intensity vector is displayed the pointer projections are proportional to the two measured horizontal components. When the total intensity vector is displayed the pointer projections are proportional to the amplitude of the total horizontal component and the vertical component.

Azimuth angles and elevation angles to sources relative to the velocity detector axes are indicated directly on the display instrument. The perpendicular axes of the instrument represent the directions of the vector components; hence, they also correspond to the axes of the underwater velocity detectors. The angular direction of the instrument pointer relative to the

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instrument axes then is the same as the direction of the intensity vector relative to the detectors. This angle can be read directly on the instrument face. True bearings to sources are found by correcting the indicated bearings for the orientations of the underwater detectors which are determined by independent means when the detectors are installed.

In developing the intensity meter, three distinct sets of equipment were constructed and tested for performing the multiplication operation and for displaying the vectors in the manner just described. These systems are described here in the order in which they were completed.

(2) Dynamometer System

The first multiplication and display system was designed around electro-dynamometer type voltmeters. It appeared from theoretical considerations which were confirmed by laboratory tests that instruments of this type designed for use with sinusoidal signals would also satisfactorily multiply two complex signals. The product, however, is registered as a needle deflection so special means for combining the products produced by different dynamometers had to be developed in order that the intensity vector could be displayed as directly as possible.

The system developed for this purpose is shown in the form of a block diagram in Figure 2. Three dynamometers were used - one for finding each component of intensity. These instruments, which consist essentially of two windings, one fixed and the other free to rotate in the field of the first due to the interaction of currents in the two windings, were operated as shown in Figure 2. The pressure signal was applied to the fixed winding of each

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dynamometer and one of the velocity signals was applied to the moving winding of each instrument. The deflection of the instrument needles was proportional to the average value of the product of the input signals and was hence proportional to the amplitudes of the intensity vector components.

The high frequency oscillator and the phase discriminators shown in Figure 2 were used to produce dc voltages proportional to the meter deflections. These voltages were needed for producing a display of the total vector. With this display the amplitude and direction of the intensity vector can be found without calculations based on the meter readings.

To produce dc voltages which were not only proportional to the amplitudes of the instrument needle deflections but also indicative of the direction of the deflections, the high frequency signal was added to the pressure signal applied to the stationary coils in the dynamometers. This signal had no influence on the positions of the instrument needles but it induced a high frequency signal in the moving winding attached to the needles. The induced voltage amplitude in each dynamometer changed as the needle rotated under the influence of the pressure and velocity signals and its phase relative to the impressed high frequency signal reversed as the needle passed its zero position where the fixed and rotating windings were at right angles. These induced voltages were impressed on the discriminators where they were converted to dc voltages with the required characteristics.

The high frequency oscillator signal was used as a reference signal in the discriminators in order that the discriminators would perform their needed function. By using this reference voltage the dc outputs

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of the discriminators were not only proportional to the amplitudes of the induced voltages but they were positive or negative depending on whether the instrument needles were deflected in a clockwise or counterclockwise direction.

The discriminator output voltages were applied to the display apparatus symbolized in Figure 2 to produce the desired vector indication. The two voltages representing horizontal components of intensity (I_{n-s} and I_{e-w}) were combined to produce a display of the total horizontal intensity component. A standard electrostatic deflection oscilloscope was used as a display instrument. One of the horizontal component voltages was applied to each of the deflection circuits. The deflection of the spot on the oscilloscope screen was thereby made to have components in the direction of the vertical and horizontal axes that were proportional to the components of the horizontal sound intensity vector.

A deflection of this sort makes a line drawn from the center of the screen to the spot position represent the horizontal intensity vector. The length of the line is proportional to the vector amplitude and the line's bearing relative to the screen axes which represent the underwater geophone axes is the same as the azimuthal bearing of the source producing the sound intensity relative to the detectors.

A similar procedure was followed in displaying the total intensity vector, but an additional piece of equipment was required. This was for producing a dc voltage proportional to the vector sum of the horizontal components. Such a voltage has to be combined with the vertical component

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voltage to produce the total vector, but none was produced when the total horizontal component was displayed.

The circuit developed for producing this voltage is labeled "triangle solving circuit" in the diagram of Figure 2. It first converts the two dc voltages representing the horizontal intensity components into two ac voltages that are ninety degrees out of phase. The amplitudes of these voltages are proportional to the amplitudes of the corresponding dc voltages. These ac voltages are added together and the sum is rectified to produce a dc voltage proportional to the sum's amplitude. Since the sum's amplitude equals the square root of the sum of the squares of the amplitudes of the other two ac voltages, the dc output is proportional to the vector sum of the dc input voltages and is therefore proportional to the amplitude of the total horizontal component of intensity.

When the switch in Figure 2 is in the elevation position this voltage is combined with the vertical component voltage in the oscilloscope to produce the total vector display. A line drawn from the spot position to the screen center in this case would have a length proportional to the total vector and its elevation above the horizontal oscilloscope axis would represent the elevation angle of the sound source relative to the detectors.

In discussing both of the vector displays the properties of a line from the spot position to the screen center were considered. In both cases the line would validly represent the vector so having it drawn would be advantageous. The line is not drawn when only dc voltages are applied to the oscilloscope, however. A single spot displaced from the screen center is all that can be seen.

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Equipment was developed to make the spot on the screen periodically trace the line from the screen center to the proper final position and thereby draw in the line. When this was done the line gave the appearance of rotating about the center of the screen as source locations changed. It also had all the other characteristics of a pointer such as the one described in the early paragraphs of this section for showing the bearing to a sound source. In addition, it indicated the intensity amplitude, a property of negligible importance in detection applications but one of considerable importance in transmission and reflection studies.

The R-C network shown in Figure 2 with shorting switches across the condensers shaped the voltages across the oscilloscope terminals to make the spot draw in the line. The switches were actually sets of contacts in vibratory chopper relays which were alternately opened and closed at a 60 cycle rate. The voltages on the oscilloscope terminals were zero when the contacts were closed and then they rose slowly to the value of the voltage applied to the networks as the condensers charged through the resistors.

The spot drew the desired line as these voltages were applied. When the voltages were reduced to zero the spot instantly jumped to the center of the screen. As the voltages increased the spot slowly moved toward the position it would have occupied if only dc voltages had been applied. Soon after it reached this point it was returned to the screen center and the path was retraced. The spot traverses a straight line path because the two voltages causing the movement always had the same relative amplitudes. This condition was established by operating the contacts in the two input circuits in synchronism and setting the time constants in the R-C networks to the same

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value. This series of events was made to recur frequently enough that a bright line pointer was produced on the face of the oscilloscope.

While this system including the dynamometers, the discriminators, and the oscilloscope input voltage shaping circuits represented a complete practical set of multiplication and display apparatus for the intensity meter, it did not represent completion of this phase of the work on the over-all project. This apparatus appeared to need improvement.

Laboratory tests showed that the main faults of this system stemmed from the use of the dynamometer multipliers. The instruments were unstable when complex signals were applied. They necessitated the use of discriminators and a stable high frequency oscillator which made the system objectionably complex. And the time constant for averaging instantaneous products of complex pressure and velocity signals could not be arbitrarily selected. This averaging time depended on the practically unalterable mechanical constants of the dynamometers. The development of the electronic multiplier to be discussed next stemmed from a desire to overcome these faults.

(3) Electronic Multiplier System

In this system the same display equipment is used but the dynamometers and discriminators of the former system are replaced by electronic multipliers. Signal amplifier output voltages are applied directly as inputs to these units and the correct dc voltages for producing pointers on the oscilloscope face are produced by them. A block diagram of this system would be identical to the one of Figure 2 with three multipliers replacing the dynamometers, the discriminators, and the high frequency oscillator of

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that figure.

These electronic multipliers were described completely in Report No. 4. They employ a new multiplication method in which the product of two input voltages is found by obtaining the average value of the difference in absolute magnitudes between two quantities formed by adding a large high frequency sawtooth carrier to both the sum and difference of the input voltages. The report shows that this difference in magnitudes is proportional to the desired product and that it can be obtained from the input with simple conventional circuits. Multipliers utilizing the new method are simple and inexpensive. They operate with high accuracy over a wide dynamic range and are stable and dependable. They are well suited for field use.

Specific reference was not made in the report to the application for which these instruments were designed so the report was unclassified and was widely distributed. Considerable interest in the multiplier has been shown. Several requests for copies of the report from industrial, governmental, and academic organizations working on analogue computing systems and systems for applying correlation techniques have been filled. Also, the author has presented papers on the multiplier before meetings of The Acoustical Society of America, The Institute of Radio Engineers, and the American Institute of Electrical Engineers. Intentions to adopt the new method were expressed in all of these cases, and it is understood that personnel at the Defense Research Laboratory in Austin, Texas have already done so in a system they are developing.

Previous discussion has already indicated how multipliers are used in the intensity meter. Construction of the instruments for this application did not take much time. The discriminators already on hand were

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converted to multipliers by simply changing the input signals applied to them. They became multipliers when the sum of the pressure signal and the sawtooth carrier was applied as one input to each instrument and one of the velocity signals was applied as the other input. The output voltages of the three discriminators which were now multipliers was proportional to the amplitudes of the directional components of intensity and they were applied to the display circuits to produce the pointers on the oscilloscope face.

The electronic multipliers had none of the faults of the dynamometer multipliers of the former system so they were used in all field tests of the intensity meter.

(4) Compass Type Indicator

The third system developed for performing the multiplication and display operations was an electromagnetic device intended to replace everything in the previous systems from the signal amplifiers on. It was a single instrument six inches square and six inches high which contained means for multiplying the pressure signal by two velocity signals and displaying the vector sum of the products. An actual rotating pointer represented the total vector.

In using this compass-like indicator two velocity signals are applied to fixed coils to produce crossed horizontal magnetic fields and the pressure signal is applied to another coil to magnetize a soft iron vane. The magnetized vane rotates about a vertical axis in the center of the instrument to become aligned with the field produced by the velocity coils. The direction of a pointer attached to the vane validly indicates the direction of the sound intensity vector.

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Report No. 6 describes the operating principles of the instrument and the development work done on it. The possibility of modifying commercially available phase angle meters and synchrosopes was first investigated and the conclusion was reached that a special instrument would have to be built. The construction and evaluation of an instrument for indicating just the azimuth angle to a sound source is discussed in the report. The instrument was found to operate as expected but it was less accurate and operated over a more limited range of input signal values than the all electronic system. These limitations were felt to stem from the rather crude mechanical bearings used for the rotating vanes and the recommendation was made that development be continued with emphasis being placed on reducing the friction in the bearings. This further development was not carried on under the contract because facilities for making better bearings were not available. Test results on this instrument did not discredit the possibility that an instrument of this type might have advantages for some applications and they did show that this third method of indicating the direction of a vector quantity was feasible.

e. Auxiliary Equipment

Input and output test panels not shown in the block diagram of the entire system were also constructed to simplify checking the system operation and to perform other beneficial auxiliary functions in the system. The input test panel contains the compensating circuit, batteries for operating the pressure detector's preamplifier, and a switching arrangement for applying tests signals at appropriate points in the system. Connectors for the cables

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leading to the underwater detectors are on this panel and terminals for applying a signal from a test oscillator are also provided on it.

The output test panel facilitates studying the output voltages of the signal amplifier and the multipliers. It has on it terminals for making connections to dc and ac vacuum tube voltmeters and other terminals for making connections to both the horizontal and vertical deflection circuits of an oscilloscope. By means of a selector switch on the panel the output voltages from every signal amplifier, from every multiplier, and from the electronic "triangle solving" circuit can be successively applied to the voltmeter terminals. By means of another selector switch the vertical deflection circuit of the oscilloscope can be connected to the voltmeter terminals so that the wave form of the selected signal can be observed. The two other positions of this second selector switch cause both of the oscilloscope input terminals to be connected to the points where either the azimuth or elevation angle to the sound source are indicated on the oscilloscope.

A low frequency test oscillator and dc and ac vacuum tube voltmeters are included with the system as standard auxiliary components. When they are permanently connected to the test panels the operation of every system component can be investigated by means of the selector switches on the panels. This facilitates trouble shooting and adjusting the system for optimum operation.

Special high quality power supplies for operating the system components were also constructed. They convert the 60 cycle, 115 volt, ac power delivered to them to regulated and unregulated 6.3 volt ac filament

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power and regulated dc power at plus 250 volts and minus 250 volts. The long time stability, the regulation with load and supply voltage variations, and the output ripple levels were made better in these power supplies than could be obtained from commercially available units with similar output capacity. The excellence of these power supplies makes it possible to operate even the first stages of the high gain signal amplifiers from them without introducing detectable hum in the amplifiers.

f. The Assembled System

In order that the system could be tested in places where no special instrument location provisions had been made, each of the system components was made as a separate small unit. The units were all housed in sheet iron boxes thirteen inches wide, seven and one-half inches high, and seventeen and one-half inches deep. Receptacles for making connections to the units and controls for operating the units are on the front panels. The units can be arbitrarily stacked and connected together for rigidity or they can be scattered about and interconnected only by the electrical cables. With this sort of arrangement the system can be maneuvered in pieces through small openings such as the hatchways in a submarine and operated for test purposes in places where a single large unit could not be tolerated.

The units were made rugged so they would not be damaged under adverse operating conditions. They were also made neat and attractive and all connectors and controls were clearly labeled. Figure 3 is a photograph of the system assembled in its most compact form. The photograph shows all the units except the underwater detectors required for measuring three components of

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sound intensity and displaying the horizontal and total intensity vectors.

Labels on the units indicate what they are.

3. System Tests

The completed system was tested in the laboratory with the detectors operating in air in an anechoic duct, at a lake with the detector suspended near the lake bottom in approximately eighty feet of water, at sea with detectors suspended above the deck of a submarine hovering at periscope depth, and at a harbor with the detectors suspended above the harbor bottom in approximately fifty feet of water. The results of these tests are summarized here.

a. Laboratory Tests

A wooden horizontal anechoic duct was constructed for these tests. It was sixteen feet long and it had a three foot square cross section. Sound absorbing fiberglass filled one end of the duct for a distance of eight feet and the walls were covered with a three inch layer of dry sand. A circular hole in the top near the point where the fiberglass started permitted insertion of test instruments into the duct.

During tests using this duct the intensity meter detectors measured the properties of sound waves propagated through it. A standard loud speaker placed at the end not containing the fiberglass transmitted sound energy down the duct. The fiberglass absorbed a portion of the energy so there was a net flow toward the fiberglass. The intensity meter detectors were elastically suspended from a circular rotatable cover for the hole in the top of the duct. The elasticity of the cords used for this suspension isolated the detectors from vibrations of the top and the walls. The detectors therefore responded to air-borne sound only and the behavior of the entire intensity

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measuring system was studied.

The studies were conducted while the loud speaker produced both sinusoidal and complex sound waves. In both of these cases the intensity vector displayed on the oscilloscope pointed in the direction representing the bearing to the sound source. Sound frequency variations in the range between 20 and 500 cps produced no changes in bearing indications. Changing the relative bearing to the sound source by rotating the detectors made the pointer on the oscilloscope rotate to indicate the new relative bearing. This result was obtained also for all sound frequency and wave shape conditions.

Other interesting results were obtained when speakers were operated at both ends of the duct. The intensity meter indication produced by energy flowing from one end could be cancelled by energy from the other end. And this could be done when the speakers were operated at the same or different frequencies or when one was driven from a sinusoidal source and the other was excited by a pure noise signal.

When energy cancellation had been obtained the speakers at each end were turned off separately. The intensity meter indication showed that the intensity vector produced by one speaker was equal in amplitude and exactly opposite in direction to the vector produced by the other speaker.

When the speakers were operated at frequencies that differed only slightly, a quite obvious "beat note" could be heard and the intensity meter indicated that energy was flowing past the detectors in first one direction and then the other. The line on the oscilloscope screen periodically

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grew to a maximum length in one direction then degenerated to zero and grew to the same length in the opposite direction. It was interesting to note the correlation between the variations in the loudness of the sound heard at one end of the sound duct and the direction and amplitude of the line on the oscilloscope. This correlation clearly indicated that sound energy flow was being measured by the intensity meter.

These results are described here because they indicated not only the suitability of the system for field use but also some unusual characteristics of the system that may make it attractive for academic sound field studies.

b. Lake Tests

The first field tests of the system were conducted at Lake Travis near Austin, Texas using facilities of the Defense Research Laboratory. The purposes of the tests were to see if the detectors operated satisfactorily under water and to see if the system indicated the bearing to a boat by measuring at a single point the complex water-borne sounds produced by the boat. The details and results of these tests were reported in Memorandum No. 1 mentioned in Section B of the report list. The tests indicated that the system operated in the manner expected. With the detectors elastically suspended from a tripod on the bottom of the lake the system pointed to a picket boat as it made radial runs at a constant bearing relative to the detectors and as it circled the detectors.

These tests conducted under conditions of very low ambient background noise also indicated that the system was ready for tests at sea where conditions would be less ideal.

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c. First Sea Tests

The instrument was expected to be useful aboard a submarine as a passive detector of enemy shipping, so arrangements were made with the Naval Electronics Laboratory at San Diego, California to test the system on a submarine assigned to that laboratory. Results of these tests and conclusions reached from them were included in Report No. 1. The detection system operated satisfactorily with the detectors hung above the submarine deck when the boat hovered and when reasonably quiet conditions existed. Fairly accurate bearings to surface ships were obtained when the surface ships were operating within a distance of over 5,000 yards from the submarine. Random traffic in the test area prevented the evaluation of bearing accuracy and the range limitations of the system. Since adverse effects from this traffic were to be expected from theoretical considerations, the results were not discouraging. They emphasized the fact that the system is best suited for passive listening applications where the sound field at the detectors is produced by a single source. Data indicative of the intensity meter's capabilities were obtained only during occasional brief periods when a situation of this type existed. These data showed that the system was suitable for low frequency directive listening. Additional evaluation tests conducted off normal traffic lanes are recommended.

d. Harbor Tests

The suitability of the intensity meter for studying the transmission and reflection of transitory sound bursts and for locating the source of the bursts was studied under the auspices of the Harbor Defense Research Unit at Beavertail Point near Jamestown, Rhode Island. This study is reported

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in Report No. 5. The responses of two systems with detectors located approximately 900 feet apart near the bottom of a ship channel were studied and compared as acoustic water-borne energy bursts from distant explosions and splashes passed the detectors. Intensity variations with time were observed on the oscilloscope and recorded simultaneously with a standard seismic oscillograph. The recordings were studied later to determine the directional characteristics of the energy bursts. With these recordings it was possible to discern intensity variations due to several sound pulses from the source and to calculate the amplitudes and directions of arrival of each packet of energy. It is expected that considering these properties of each received pulse would give information on reflection and propagation phenomena that would be quite difficult to obtain by other methods. The intensity meter, therefore, is attractive as a tool for use in fundamental underwater sound studies.

When smooth records indicated that only energy traveling in the direct path appreciably influenced the intensity variations, the system could be evaluated as a splash and explosion locator. Assuming that in most applications the detectors could be located where reflections would have a negligible effect, the conclusion was reached that the system could be profitably used in acoustic minewatching. Only minor additions to the system are needed to make it operate as a continuous automatic monitor and the tests indicated that the system gives the bearings to splash locations to an accuracy of better than ± 5 degrees when the splashes occur within 3,000 yards of the detectors. The system operates satisfactorily in the presence of continuous

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noise such as that caused by inclement weather or normal harbor ship traffic. Since a single detector gives bearing data, very few relatively simple and inexpensive detector installations could watch over a large area.

Further development of the system and additional evaluation for harbor defense applications are strongly recommended.

4. Conclusions on the Intensity Meter Development

The development reported here is considered to represent complete fulfillment of the Magnolia Petroleum Company's technical obligations on the intensity meter phase of the contract. The proposed system was assembled and its usefulness for passive listening applications was studied.

It is felt also that benefits beyond those specifically expected were derived from the development. The instrument turned over to the ONR can be used for further test work or it can be used as a prototype for other systems constructed for either test or permanent installation. In designing the components needed for the intensity meter, circuits and techniques which promise to be useful in other systems were developed. Most prominent of these were the small low frequency directive detector assembly and the electronic multiplier.

The field tests which demonstrated the possible usefulness of the intensity meter for passive detection of either continuous or transitory low frequency sound sources also suggested other uses for the system. For example, it probably can be used for directive detection installed in a sonobouy which would radio the direction information back to an operation base; it might even be useful for directive listening in an acoustic homing device where small detector size and low frequency operation are extremely important; and since

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the system has been shown to point satisfactorily when transitory sounds energize the detectors, it can be useful as a detector in an active low frequency sonar system.

In addition to suggesting these other uses, the tests established the feasibility of measuring intensity for locating sound sources. This is a new method of detection which might be profitably applied to systems employing other detectors and operating at higher frequencies.

B. The Impedance Meter Development

The impedance meter is an example of a system advantageously using components and techniques developed on the intensity meter phase of the project. It involves detectors similar to those used with the intensity meter; identical compensation circuits are required by both systems; and an electronic multiplier like those of the intensity meter performs an operation in the impedance meter that gives the latter instrument one of its most unusual and attractive characteristics. The impedance meter development was appreciably advanced by having these components already available.

The work on the impedance meter, however, involved more than just assembling the components into a neat package. While this was a part of it, the development also involved designing additional special components. These were intended to make the system a practical and handy one for using a direct and very fundamental, but rarely used, method of measuring impedance. In this impedance meter, sound pressure at a point is compared with particle velocity at the same point. In order that impedance phase angles could be read directly, a network was developed that produced the same phase shift between two sinusoidal

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signals at all frequencies. This phase shift was made adjustable from plus 90 degrees to minus 90 degrees and because its effect was independent of frequency the control could be (and was) calibrated in degrees. A special three-phase oscillator was designed for use in conjunction with this phase shift circuit and it serves double duty by supplying also the single phase voltage for operating the sound projector needed for the impedance measurements.

Use of the multiplier also simplifies the system and the operating procedure. It is used for producing an output voltage proportional to the amplitude and phase of a single selected frequency component of the received pressure and velocity signals. This makes accurate operation of the instrument possible when the noise level at the detectors is high or when the output of the test sound projector is a series of recurrent pulses or some other non-sinusoidal wave shape.

Report No. 8 describes the impedance meter. It explains the operating principles of all the system components; it gives instructions for testing the system and taking impedance data; and it clearly points out the attractive features and the limitation of the system. Test data indicating that the instrument accurately measures the impedance of reflecting interfaces is also presented.

While the impedance meter development was a minor phase of the work on the project reported here, the instrument is a complete system that is expected to have wide usefulness in studying low frequency, underwater sound, transmission, and reflection phenomena. It was specifically designed for measuring bottom impedances but by replacing the vertically sensitive velocity detectors in the pickup assembly with an horizontally sensitive unit the system's

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usefulness can be extended. The low frequency impedance of ships' hulls and other vertical reflectors could then be measured also.

This system too embodies components and techniques that can probably be used elsewhere. Several other possible applications for the three-phase oscillator and the calibrated phase shift circuit have already occurred to workers on this project, and the possibility of using the multiplier section separately as a harmonic analyzer has also been considered. Another possible use for the instrument is as an electrical impedance meter. For this use voltage signals would replace pressure signals and current signals would replace velocity signals. As an electrical impedance meter the system would be unusual from the standpoint that complex test signals could be applied to the impedance under test.

IV. CLOSURE

The purpose of this report was to summarize the accomplishments under Contract Nonr-580(00). It describes the construction and preliminary evaluation of two low frequency systems which advantageously utilize underwater sound properties that have been disregarded previously. Also, several techniques and circuits which are expected to be useful in systems besides the ones for which they were specifically designed were discussed. These last accomplishments were included to point out that benefits beyond those intended were derived from the work.

In the light of this fact and the fact that the completed systems were shown to have several attractive operating characteristics, it would seem that the development should be continued. A proposal to do this has not won support,

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however, so the Magnolia Petroleum Company Field Research Laboratories will not continue the work.

This report then summarizes the complete contribution of these laboratories on the intensity and impedance meters, and unless apparent intentions are changed, it represents all the work that will be sponsored by naval activities on these promising systems.

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APPENDIX

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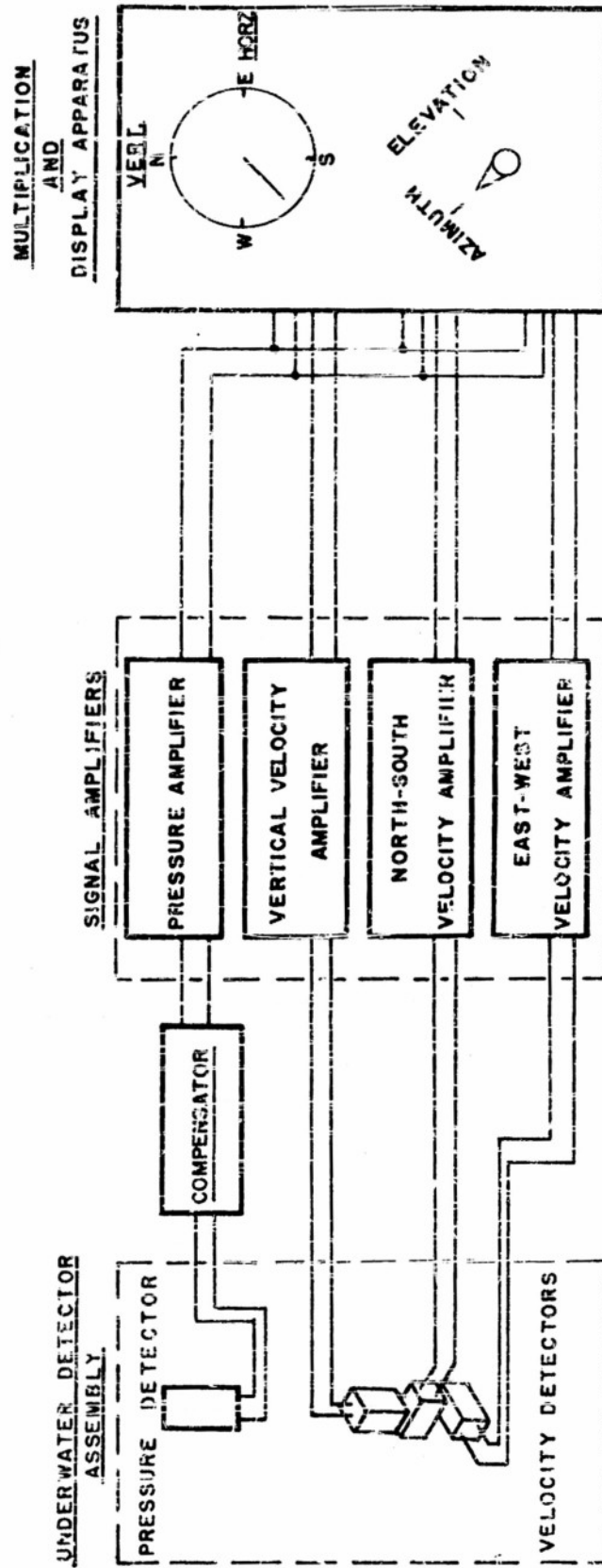
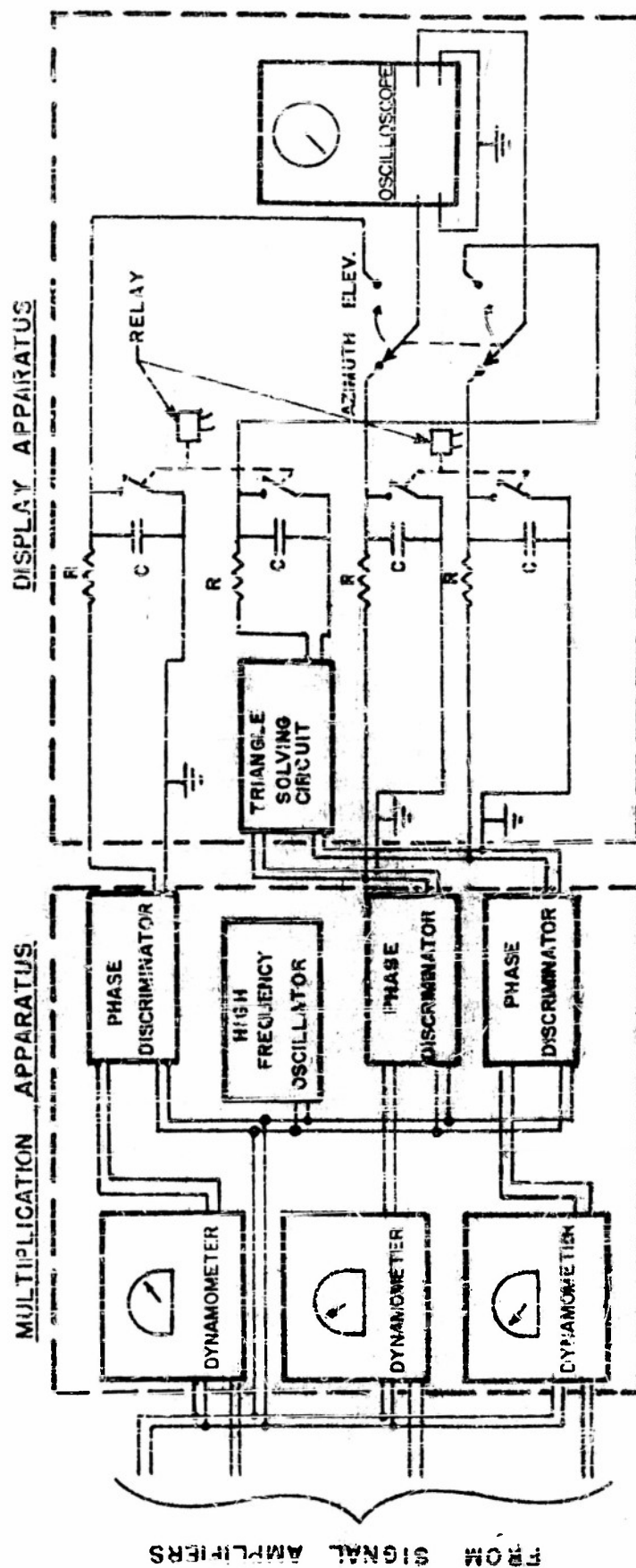


FIGURE 1
BLOCK DIAGRAM OF
INTENSITY METER

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FIGURE 2

BLOCK DIAGRAM OF DYNAMOMETER

MULTIPLICATION AND DISPLAY SYSTEM

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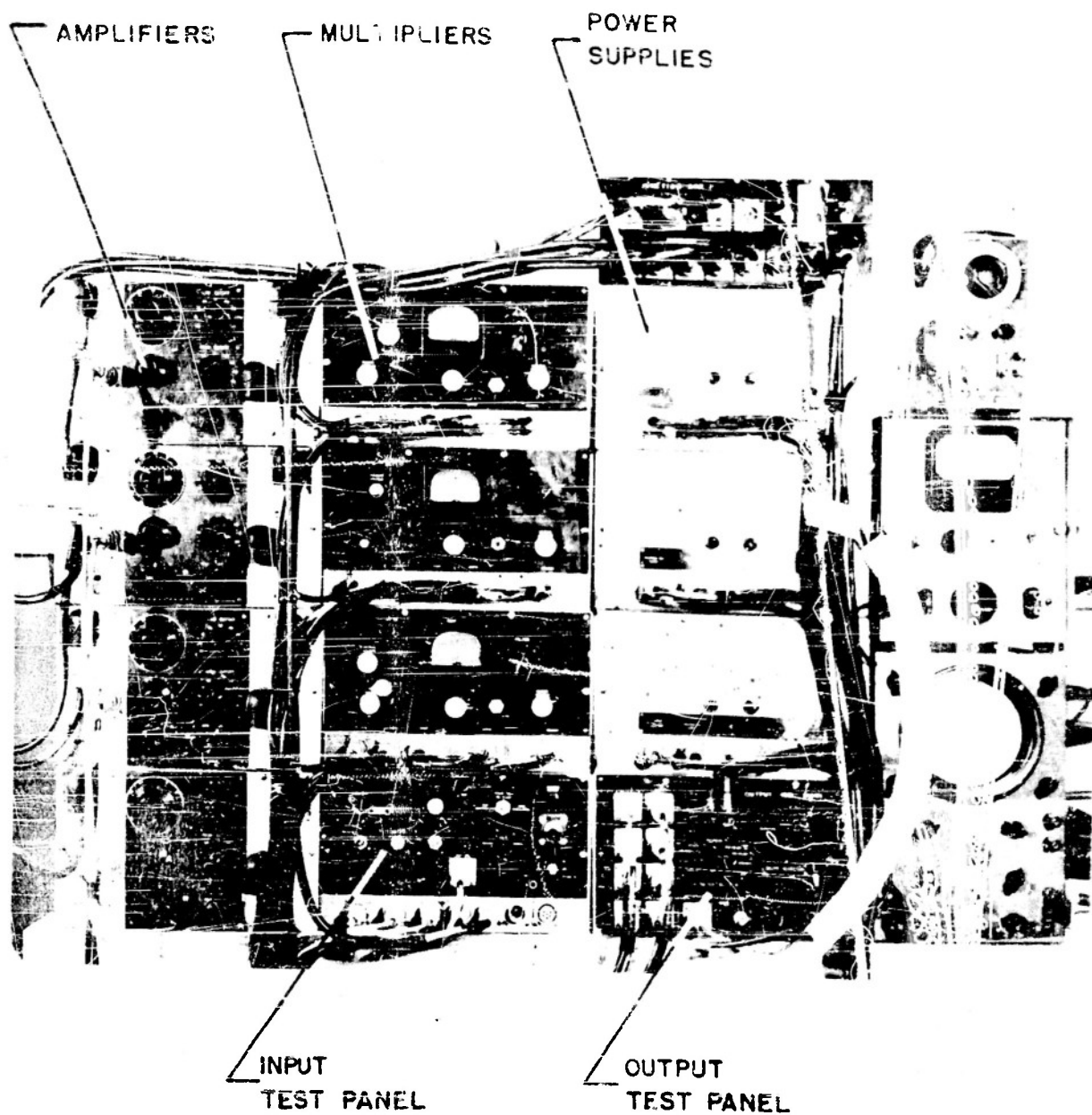


FIGURE 3
PHOTOGRAPH OF 3-COMPONENT
INTENSITY METER INSTRUMENTS

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